3D hydrogeological modelling at a mining development site with complex hydrostratigraphy in northern Finland

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Punamusta
Joensuu 2021

67°30'02" pohjoista leveyttä
ja 26°40' itäistä pituutta ilman sekstanttia
osapuilleen runo Kitisen rannalla
kun Kotisuvannosta jäät
kun sauvoimet ja soukat veneet ja tervan haju
kun Kotiaavalla kurki
ja villihanhet yli.

…

> *Pakolliset kuviot*
> *voimalaitokset kaukana vielä*
> *monen vuoden takana etelässä:*
> *satatuhatta tai miljoona litraa vettä sekunnissa*
> *nivan kohdalla Poronkuvanivan*
> *jättiläistelejä Kitisen rannalla Suurin Kirjaimin.*

Nousviikolla kesä.

Excerpts from Veikko Haakana's poem Jonain iltana yönä aamulla from 1972

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Abstract

There is an increase in mining projects in northern regions in the areas of complex Quaternary sediments overlaying weathered bedrock, where groundwater systems are understudied. This study increase the understanding of the interaction of surface and groundwaters in an ecologically sensitive northern area where mining and other human activities occur.

Groundwater and surface water interactions in riverbanks and open mire areas are critical environments of groundwater-dependent ecosystems (GDEs). Mires are a prevailing feature in northern boreal and subarctic regions, and their interactions with groundwater and other surface water systems are usually poorly understood. If nutrient-rich fens are located in an area where mining activities are planned to take place, a detailed understanding of the water balance and groundwater discharge and recharge patterns are needed, especially how groundwater is linked to properties of the subsurface sediments. Northern areas glaciated and located in weak glacial erosion areas during the last ice ages, could form a complex sedimentary succession interlayered with low-conductivity till and variable sorted sediments having hydraulic conductivity that is orders of magnitudes higher. The glacial–interglacial cycles can enable the formation of highly heterogeneous and scattered sediment units, which are challenging to model.

The study area is located in the western part of a Natura 2000-protected Viiankiaapa mire, which lies above a high-grade and significant Ni-Cu-PGE deposit. The hydrology of the regulated River Kitinen nearby affects the western part of the Viiankiaapa mire, presumable supporting the habitats of groundwater-influenced mire species. The construction of hydroelectric power plants and river regulation have changed the hydrology of the study area from the 1970s onwards. The first objective of this study was to 1) characterize the groundwater recharge/discharge and flow patterns of groundwater in Quaternary sediments and shallow bedrock, 2) examine the effect of hydrostratigraphic complexity on groundwater recharge/discharge and flow patterns, and 3) investigate the effect of river regulation on the hydrology of the Viiankiaapa mire and the habitats of groundwater-influenced mire species. The second objective of the study was to create a workflow for 3D groundwater flow modelling suitable for baseline studies located in weak glacial erosion areas. The 3D groundwater flow modelling was applied to model the groundwater recharge/discharge patterns of the study area. Flood modelling was used to model the pre-regulation flood coverage of the study area and to evaluate its effect on the present habitats of groundwater-influenced mire species. Stable isotopes of water and thermal imaging with an unmanned aerial vehicle were used to determine groundwater discharge locations and to verify the groundwater flow models.

The results of groundwater flow modelling indicated that water from the Viiankiaapa mire flows towards the River Kitinen and discharges locally within the mire area and along the shoreline of the river. Groundwater recharge/

discharge and flow patterns were affected by the high complexity of the hydrostratigraphy of surficial deposits, weathered/fractured bedrock, and small-scale topographical variation within the mire area.

The results indicated that high variation in hydraulic conductivities dispersed recharge/discharge patterns in hydrostratigraphically detailed models compared to more simple models. The weathering profile of the fractured bedrock and the variation in hydraulic conductivity were also found to be important in modelling the connections of shallow groundwater in sediments and in the topmost part of the bedrock.

Construction of the Matarakoski and Kelukoski power plants in the River Kitinen affected the hydrology of the study area by reducing spring floods and by raising the river stage. The river stage rise caused a reduction in the hydraulic gradient towards the River Kitinen. The reduction in the hydraulic gradient raised the water table, increased groundwater discharge in the western part of the mire and decreased groundwater discharge into the River Kitinen. Furthermore, the modelling results indicated that half of the present habitats of the studied groundwater-influenced plant species occur in areas affected by the regulation of the river.

The major phases of the created workflow were 1) definition of the hydrostratigraphy based on the differentiation of glacial tills and interlayered sorted sediments, 2) the use of models such as MODFLOW-NWT, allowing the modelling of unconfined settings in the model, and 3) modification of the hydrostratigraphy of the model based on calibration, evaluation and verification results in an iterative manner. According to the results of this study, constructing a 3D geological model and a 3D groundwater flow model is giving valuable support for baseline studies and in the early planning stages of mining. The understanding of past and present anthropogenic influences can be valuable for these baseline studies.

Tiivistelmä (in Finnish)

Kaivosprojektien määrä on lisääntymässä pohjoisilla alueilla, joissa kompleksiset kvartäärisedimenttikerrostumat peittävät rapakalliota ja joissa alueen pohjavesivarastot tunnetaan usein heikosti. Tämän tutkimuksen tarkoituksena on lisätä ymmärrystä pohjavesien ja pintavesien liikkeistä ja vuorovaikutuksista ekologisesti herkillä pohjoisilla alueilla, joissa on kaivostoimintaa tai sen suunnittelua, taikka muuta ihmisen toimintaa.

Pinta- ja pohjaveden vuorovaikutus on tärkeää tunnistaa, sillä jokien ranta-alueilla ja aapasoilla on usein tärkeitä pohjavesivaikutteisten ekosysteemien esiintymisalueita. Aapasuot ovat yleisiä pohjoisella boreaalisella vyöhykkeellä, mutta niiden yhteys muihin vesistöihin ja pohjavesivarastoihin on usein huonosti tunnettu. Mikäli ravinnerikkaille lettoalueille suunnitellaan kaivostoimintaa, tarvitaan yksityiskohtaista tietoa ja ymmärrystä paikallisesta vesitaseesta sekä pohjaveden muodostumis- ja purkautumiskuvioista, jotka linkittyvät suoraan maaperän rakenteeseen. Pohjoiset alueet ovat jäätiköityneet toistuvasti viimeisten jääkausien aikana synnyttäen monimutkaisen sedimenttisukkesion. Heikon jäätikön kulutuksen alueella vuorottelevat alhaisen vedenjohtavuuden moreenit ja vaihtelevat lajittuneet sedimentit, joilla on usein moreeneja selvästi korkeampi hydraulinen johtavuus. Glasiaali-interglasiaalisyklien synnyttämät vaihtelevat ja hajanaiset sedimenttiyksiköt ovat hydrogeologisen mallinnuksen kannalta haastavia ympäristöjä.

Tutkimusalue sijaitsee Natura 2000 -suojellun Viiankiaapa nimisen aapasuon alueella, jonka alapuolella on rikas Ni-Cu-PGE esiintymä. Aapasuon vieressä virtaava säännöstelty Kitisen joki vaikuttaa hydrologialtaan Viiankiaavan läntiseen osaan, jossa esiintyy oletetusti pohjavesivaikutteisia ekosysteemejä. Vesivoimalaitosten rakentaminen ja jokien säännöstely ovat muuttaneet tutkimusalueen hydrologiaa 1970-luvulta lähtien. Tutkimuksen ensimmäinen tavoite oli 1) karakterisoida pohjaveden muodostuminen/purkautuminen ja virtauskuviot maaperän pohjavesisysteemissä ja kallion ylimmässä osassa, 2) tutkia maa- ja kallioperän hydrostratigrafisen mallin kompleksisuuden lisäämisen vaikutusta mallinnettuihin pohjaveden muodostumis/purkautumis- ja virtauskuvioihin, ja sekä 3) selvittää, miten joen säännöstely on vaikuttanut Viiankiaavan hydrologiaan ja pohjavesivaikutteisten suokasvilajien esiintymiin. Toinen päätavoite oli kehittää heikon jäätikön kulutuksen alueelle sijoittuville kaivostoiminnan suunnittelualueille soveltuva 3D-pohjaveden virtausmallinnuksen työnkulku. 3D-pohjaveden virtausmallinnusta sovellettiin pohjaveden muodostumis/purkautumis- ja virtauskuvioiden mallintamiseen tutkimusalueella. Tulvamallinnusta käytettiin puolestaan säännöstelyä edeltävän tulvan vaikutusalueen laajuuden selvittämiseen ja sen arvioimiseen, miten tulviminen on vaikuttanut suoalueen pohjavesivaikutteisten kasvien esiintymiin. Veden hapen ja vedyn stabiileja isotooppeja ja lämpökamerakuvausta miehittämättömällä lentoalustalla hyödynnettiin pohjaveden purkautumisalueiden tunnistamiseen sekä pohjaveden virtausmallien verifioimiseen.

Pohjaveden virtausmallinnusten tulosten perusteella pohjavesi virtaa tutkimusalueella pääasiassa suolta kohti Kitistä. Viiankiaavalla osa suovedestä imeytyy pohjavesivyöhykkeeseen ja virtaa kohti Kitistä purkautuen paikoin suolla ja joen rannan lähteissä. Pohjaveden muodostumis/purkautumis- ja virtauskuvioihin vaikuttaa maaperän kerrosten hydrostratigrafinen rakenne, kallioperän pintaosan rikkonaisuus ja rapauma sekä topografian vähäiset vaihtelut suolla.

Pohjaveden virtausmallien tulosten mukaan maa- ja kallioperän hydraulisen johtavuuden suuri vaihtelu on keskeinen syys siihen, että pohjaveden muodostumis/purkautumiskuvio on yksityiskohtaisempi ja hajaututempi hydrostratigrafisesti yksityiskohtaisemmissa malleissa kuin yksinkertaisemmissa malleissa. Rapakallion esiintyminen ja luonne vaikuttavat maaperän pohjaveden ja kallion pohjaveden yhteyksiin, sillä rapautuneen kallion hydraulinen johtavuus vaihtelee paljon riippuen sen rapautumisasteesta.

Matarakosken ja Kelukosken vesivoimalaitosten rakentaminen on muuttanut tutkimusalueen hydrologiaa vähentäen joen tulvimista ja nostaen joen vedenpinnan tasoa. Joen vedenpinnan tason nousu on loiventanut pohjaveden hydraulista gradienttia kohti jokea. Hydraulisen gradientin muutos on puolestaan nostanut pohjaveden pintaa ja lisännyt pohjaveden purkautumista suon länsilaidalla samalla vähentäen pohjaveden purkautumista Kitiseen. Mallinnustulokset osoittavat lisäksi, että joen säännöstelyn aiheuttamat muutokset ovat muuttaneet pohjaveden pintaa alueilla, joissa tutkittuja pohjavesivaikutteisia lajeja esiintyy yleisesti.

Kehitetyn 3D-pohjaveden virtausmallinnuksen työnkulun pääkohtina ovat 1) määrittää maaperän ja kallioperän hydrostratigrafiset yksiköt perustuen jäätikön synnyttämiin moreeniyksiköihin ja niiden välissä esiintyviin lajittuneisiin sedimentteihin sekä kallioperän rikkonaisuusvyöhykkeisiin, 2) käyttää vapaan akviferin mallinnukseen sopivia mallinnuskoodeja kuten MODFLOW-NWT:tä ja 3) muuttaa hydrostratigrafista rakennetta perustuen pohjaveden virtauksen mallinnus-, kalibrointi- ja verifiointituloksiin iteratiivisella tavalla. Tämän tutkimuksen tulokset osoittavat, että 3D-geologinen mallinnus ja 3D-pohjaveden virtausmallinnus ovat yhdessä käyttökelpoinen työkalu, jota voidaan hyödyntää jo kaivostoiminnan suunnitellun alkuvaiheessa. Pohjaveden ja vesistöjen yhteyksien karakteisoinnilla sekä tutkimalla historiallisen ja nykyisen ihmistoiminnan vaikutusta alueen hydrologiaan ja hydrogeologiaan voidaan saavuttaa arvokasta tietoa jo perustilatutkimusvaiheessa.

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Contents

List of original publications

This thesis is based on the following publications:

I Åberg, S.C., Korkka-Niemi, K., Rautio, A., Salonen, V.-P. & Åberg, A.K. 2019. Groundwater recharge/discharge patterns and groundwater–surface water interactions in a sedimentary aquifer along the River Kitinen in Sodankylä, northern Finland. Boreal Environment Research 24, 155–187.

II Åberg, S.C., Åberg, A.K., & Korkka-Niemi, K. 2021. Three-dimensional hydrostratigraphy and groundwater flow models in complex Quaternary deposits and weathered/fractured bedrock: evaluating increasing model complexity. Hydrogeology Journal 29, 1043–1074.

III Åberg, S.C., Korkka-Niemi, K., Rautio, A. & Åberg, A.K. The effect of river regulation on groundwater flow patterns and the hydrological conditions of an aapa mire in northern Finland (Submitted to Journal of Hydrology: Regional Studies).

The publications are referred to in the text by their roman numerals.

Author's contribution

I The study was designed by K. Korkka-Niemi and S.C. Åberg. S.C. Åberg constructed the groundwater flow models and prepared most of the figures and the tables. A. Rautio prepared the isotope-related figures, and A.K. Åberg the geological model-related figures. S.C. Åberg performed the statistical analyses related to groundwater monitoring data. The manuscript was jointly written by S.C. Åberg and K. Korkka-Niemi, with contributions and comments from the co-authors.

II The study was designed by all the authors. S.C. Åberg was responsible for the construction, calibration and verification of the groundwater flow models. S.C. Åberg produced groundwater flow modelling-related figures and tables. A.K. Åberg had the main responsibility for the geological/hydrostratigraphic models. However, S.C. Åberg participated in every model designing to a varying degree and was designing the hydrostratigraphic units used for the groundwater flow models. The manuscript was jointly written by all the authors.

III The study was designed by S.C. Åberg and K. Korkka-Niemi. S.C. Åberg constructed the groundwater flow models and flood models and prepared most of the figures and tables. A. Rautio prepared the isotope-related figures, and A.K. Åberg the geological model-related figures. The geological/hydrostratigraphic model was mainly constructed by A.K. Åberg in co-operation with S.C. Åberg. The manuscript was jointly written by S.C. Åberg and K. Korkka-Niemi, with contributions and comments from the co-authors.

Publications wrote within the degree but not included in thesis

Åberg, A. K., Salonen, V-P., Korkka-Niemi, K., Rautio, A., Koivisto, E. & Åberg, S. C. 2017. GIS-based 3D sedimentary model for visualizing complex glacial deposition in Kersilö, Finnish Lapland. Boreal Environment Research. 22, p. 277–298.

Åberg, S., Åberg, A., Korkka-Niemi, K., Salonen, V.-P. 2017. Hydrostratigraphy and 3D Modelling of a Bank Storage Affected Aquifer in a Mineral Exploration Area in Sodankylä, Northern Finland. – In: Wolkersdorfer, C.; Sartz, L.; Sillanpää, M. & Häkkinen, A.: Mine Water & Circular Economy (Vol I). – p. 237–244.

Abbreviations

CLGB	**C**entral **L**apland **G**reenstone **B**elt
DEM	**D**igital **e**levation **m**odel
e.g.	*__e__xempli __g__ratia*
EIA	**E**nvironmental **i**mpact **a**ssessment
ELY centre	**E**linkeino-, **l**iikenne-, ja **y**mpäristökeskus (Centre for Economic Development, Transport and the Environment
EMR	**E**pisodic **m**aster **r**ecession curve method
et al.	***et a**lia*
GDE	**G**roundwater-**d**ependent **e**cosystem
GIE	**G**roundwater-**i**nfluenced **e**cosystems
GPR	**G**round **p**enetrating **r**adar
GUI	**G**raphical **u**ser **i**nterface
K	Hydraulic conductivity
LiDAR	**L**ight **d**etecting and **r**anging
m a.s.l.	**M**etres **a**bove **s**ea **l**evel
NLSF	**N**ational **L**and **S**urvey of **F**inland
SWE	**S**now **w**ater **e**quivalent
UAV-TIR	**U**nmanned **a**erial **v**ehicle **t**hermal **i**nfra**r**ed
UPW	**Up**stream **W**eighting package in MODFLOW
WTF	**W**ater **t**able **f**luctuation method

List of figures

Errors and corrections in published Paper I

In page 160 line 36: m s^{-1} → m s^{-2}
In page 168 line 19: mm $month^{-1}$ → mm $year^{1}$

1. Introduction

Groundwater flow and groundwater recharge/discharge patterns are important parts of the hydrological cycle and need to be acknowledged at mining development sites. Moreover, groundwater discharge areas are essential habitats of groundwater-dependent (GDE) or groundwater-influenced ecosystems (GIE), and their identification is important to reduce potential risks and impacts of mining activity on the environment. Mining activities influence the quantity and quality of the water within the mine area and its surroundings, changing the hydrological and topographical conditions and affecting groundwater flow (Punkkinen *et al.* 2016). On the other hand, understanding the water balance is critical in planning, designing and positioning mining activities, and this needs to be carefully considered in environmental impact assessment (EIA) (Marandi *et al.* 2014, Salonen *et al.* 2014, Krogerus and Pasanen 2016, Punkkinen *et al.* 2016). In recent years, sustainable development and the management of groundwater resources in mining-affected areas have been acknowledged (Raghavendra and Deka 2015). Green mining projects should consider environmental aspects in all project phases, from early exploration to mine closure (Nurmi and Wiklund 2012, Nurmi 2017). Attention has also been directed to understanding the geological complexity of mining environments from a hydrogeological perspective (Artimo *et al.* 2004, Wycisk *et al.* 2009, Salonen *et al.* 2014). Understanding the circulation of groundwater and its connections to surface water, wetlands and possible fractured and weathered bedrock aquifers in baseline studies increases the transparency and thus the social licence to operate in environmentally sensitive areas.

The Central Lapland Greenstone Belt (CLGB) is the largest mafic volcanic providence in Fennoscandia (Eilu *et al.* 2012) with a high ore potential and considerable mining interest. Multiple active mines, such as Kevitsa and Kittilä, ongoing mining projects such as Sakatti, and numerous claims, exploration permits and reservations are located within the area (Fig. 1). The CLGB coincides with an ice divide area having had relatively weak glacial erosion during last ice ages (Hirvas 1991, Pulkkinen 1983, Ebert *et al.* 2015). Due to weak glacial erosion, weathered bedrock has been preserved on the top of the fractured upper part of the crystalline bedrock (Hirvas 1991, Hall *et al.* 2015), enabling interaction of the shallow groundwater with groundwater in the bedrock. The Quaternary surficial deposits consist of scattered interlayered till and sorted units, which are typical of river valleys in central Lapland (Lahermo 1970). The combination of scattered fluvial and glacigenic sediments with weathered and fractured bedrock creates complex aquifer-aquitard systems in extensive mine prospecting and reservation areas in the CLGB, causing groundwater flow patterns that are challenging to estimate. The complexity of shallow groundwater systems and their connection to weathered and fractured bedrock should be carefully considered in the environmental impact assessment of mining projects located in weak glacial erosion areas.

Surface water bodies are an abundant feature in central Finnish Lapland, and rivers with their outwash plains are common (Lahermo 1973). Operating mines and exploration areas (Fig. 1) are often located close to surface water bodies and open mire ecosystems. However, the rivers in Lapland are rarely in a natural state. The construction of the hydroelectric power plants and regulation of the rivers have changed the hydrology of the catchment areas. Moreover, most of the mires in Finland have been drained since the 1950s (Aapala 2001, Ruuhijärvi and Lindholm 2006), which has been observed to affect the groundwater discharge patterns in mire areas (Rossi *et al.* 2012).

Recognizing the potential habitats of GDE that are commonly related to groundwater–surface water interaction areas or mire areas has become an objective required by the Groundwater Directive (EC 2006) and by law in Finland since 2014 (Act on Water Resources Management 1263/2014). Groundwater supports a high level of biodiversity and provides habitats in many endangered GDEs in wetlands (e.g., Kløve *et al.* 2011, Aldous and Bach 2014). The hydrology of patterned fen/mire complexes depends on surface water runoff, snow melt, precipitation, groundwater discharge and spring floods (Lappalainen 1970, Siegel and Glaser 1987, De Mars *et al.* 1997, Ruuhijärvi and Lindholm 2006, Acreman and Holden 2013, Isokangas *et al.* 2017). Surface water inflow and groundwater discharge enhances the nutrient level in fens, enabling more diverse habitats for plants (Malmer 1986, Siegel and Glaser 1987). However, Laitinen *et al.* (2005) noted that the changes in groundwater flow patterns and discharge in wetland areas such as in fen/mire complexes have been inadequately studied. Furthermore, the composition of the sub-peat sediments is important, since the existence of a high conductivity zone beneath a mire enhances the vertical flow, creating spatial variation in groundwater discharge and recharge areas (Siegel 1988, Reeve *et al.* 2000). The hydrology of a mire complex can be affected by variation in the river stage related to natural flooding or river regulation if the mire is located in the proximity of a river.

Groundwater flow modelling is commonly used to study the groundwater interactions with surface water, as well as groundwater recharge, discharge and flow patterns (Freeze and Whitherspoon 1967, Scibek *et al.* 2007, Barthel and Banzhaf 2016). Groundwater flow modelling is suitable for sensitive areas, as it can be used to investigate the water balance and groundwater flow patterns and make predictions for future changes (Marandi *et al.* 2013) in a non-destructive manner. In addition, groundwater flow model results can reveal the potential environmental risks of anthropogenic activities if the hydrostratigraphic details of the model are adequate. This hydrostratigraphic detail depends on the research questions, data and time available for model construction (Ross *et al.* 2005). Modelling codes that can create hydraulic conductivity (K) fields based on pseudo-genetic models such as braided river bar structures can be used to construct detailed models (Bennett *et al.* 2019). In contrast, simple models are faster to produce and better serve strict schedules. However, if more time is used for the hydrostratigraphic details of a model to increase the knowledge of model area and to reduce the potential future risks and environmental impacts.

The hydrostratigraphic complexity, variation and distribution of hydraulic conductivity zones and topographical variations are the most important features affecting the location of groundwater discharge and recharge patterns (Freeze and Whitherspoon 1967, Freeze and Cherry 1979, Hayashi and Rosenberry 2002). In flat-lying areas, even small topographic variation can impact on groundwater recharge/discharge patterns (Freeze and Whitherspoon 1967, Reeve *et al.* 2000). For example, in patterned fens, variation in strings and flarks generates small-scale groundwater recharge and discharge areas (van der Ploeg *et al.* 2012). Subsurface complexity affects the groundwater flow pattern due to refraction of the flow lines in locations of K change (Freeze and Cherry 1979). The refraction causes complex flow patterns in highly variable K areas and disperses recharge and discharge areas (Freeze and Cherry 1979, Reeve *et al.* 2000).

1.1. Research aims

The first objective of this doctoral study was to: A) understand the factors affecting recharge/discharge and flow patterns of shallow groundwater and bedrock groundwater and their interactions with surface water in the study area in central Finnish Lapland, B) examine the effect of hydrostratigraphic complexity on groundwater recharge/discharge and flow patterns, and C) investigate the effect of river regulation on the hydrology of mires and habitats of groundwater-influenced mire species by comparing the present situation with the pre-regulation situation. 3D groundwater flow modelling and flood modelling were used to examine the present and past affects on the hydrology of the Viiankiaapa mire.

The second objective of the study was to create a workflow for hydrostratigraphic and groundwater flow modelling adequate for baseline studies of mining development sites in recently glaciated areas with a complex hydrostratigraphy consisting of shallow groundwater interacting with surface water and bedrock groundwater in weathered/fractured bedrock.

2. Description of the study site

2.1. Geological and hydrological background

The study site is located in northern Finland in the municipality of Sodankylä, in the western part of the Natura 2000-protected Viiankiaapa mire in a formerly glaciated area that is characterised by weak glacial erosion (Fig. 1b). A prominent Cu-Ni-PGE mineralization called Sakatti has been found underneath the Viiankiaapa mire (Brownscombe *et al.* 2015). The Sakatti deposit is situated in the CLGB, which consists of Paleoproterozoic sedimentary and volcanic rocks (Brownscombe *et al.* 2015), including quartzites, mica schists and gabbros (Tyrväinen 1980, Pulkkinen 1983, Tyrväinen 1983). The uppermost part of the crystalline bedrock is partly highly weathered and fractured (Pulkkinen 1983, Paper II).

According to Lahermo (1973), outwash plains are the most abundant groundwater reservoirs of the study area. Weathered and fractured bedrock is covered with alternating Quaternary tills and sorted sediments mainly consisting of fluvial and glaciofluvial deposits and aeolian clastic sediments often covered with peat deposits (Åberg A.K. *et al.* 2017). Groundwater reservoirs are scattered and confined and perched units also occasionally occur (Paper I). The multiple till layers originate from separate Weichselian glacial events (Åberg A.K. *et al.* 2017). The aquifer-aquitard system can be complex due to existing subtill sands, gravels and gyttja layers, as described in Åberg A.K. *et al.* (2017). Minerogenic Quaternary deposits are overlain by peat deposits in the Viiankiaapa and Vanttioaapa mire areas. The area is topographically relatively flat with altitude variation from about 180 to 207 metres above sea level (m a.s.l.).

The study area is located in a boreal and subarctic region. The mean annual temperature at Sodankylä is -0.4 °C and the June and January average temperatures are +15 °C and -12 °C, respectively (http://ilmatieteenlaitos.fi/vuositilastot [In Finnish]). The average annual precipitation in the Sodankylä area is 500–650 mm yr^{-1}, of which about half falls as snow, usually from November to May (http://ilmatieteenlaitos.fi/vuositilastot [In Finnish]). Mean evaporation was about 320 mm yr^{-1} between 1960 and 2011 (Moroizumi *et al.* 2014).

The water balance of the study area is positive, since annual precipitation exceeds the evaporation rate, and groundwater recharge dominates within the valley of the River Kitinen. The River Kitinen and other smaller rivers are mainly gaining rivers. The main groundwater recharge occurs from April to September. The high-

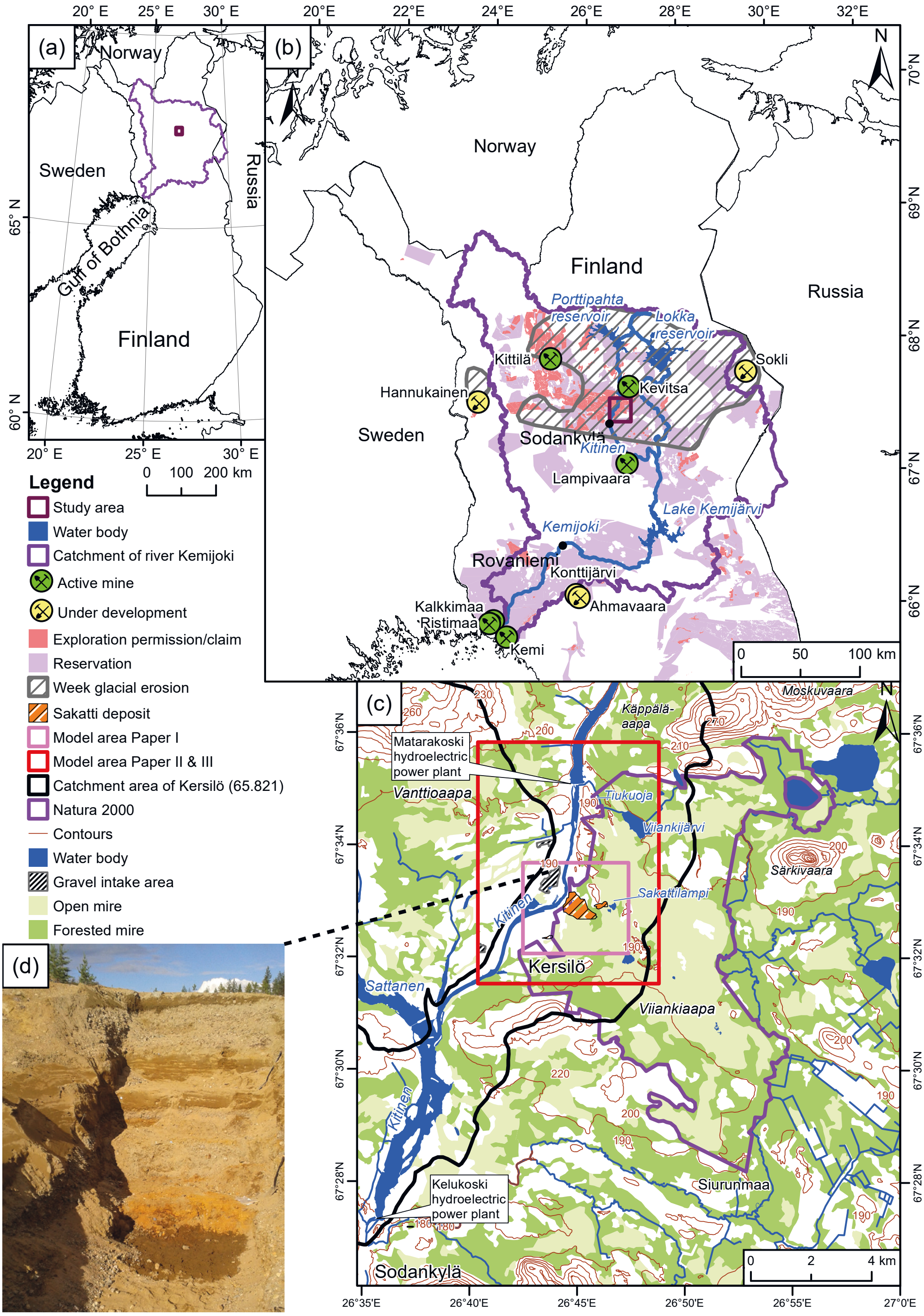


Figure 1. (a) The location of the study area presented with the catchment area of the Kemijoki river and ongoing mining projects (2020) and reservations (2011–2021). (b) Weak glacial erosion areas indicate areas with possibly complex stratigraphy and preservation of weathered bedrock. (c) The model areas and the study area in closer view. (d) Outcrop of the Kärväsniemi stratigraphic site (Åberg A.K *et al.* 2020), which was used as basis for the definition of hydrostratigraphic units of the models. Water bodies and catchment areas are modified after the Finnish Environment

Institute. The administrative borders of Finland, base maps and terrain elements were modified after the National Land Survey of Finland (NLSF). Mines and exploration are modified after the Geological Survey of Finland. Exploration permission/claims and reservations ©Finnish Safety and Chemical Agency TUKES. Weak glacial erosion is modified after Ebert *et al.* (2015). Sakatti deposit is modified after Pöyry (2018). Administrative borders of Sweden, Norway and Russia, source GADM 2020. Figure (d) photography: ©Annika Åberg. The coordinate system is EUREF-FIN TM35.

est recharge rate in spring results from the spring thaw and the secondary maximum results from intense rainfall in summer and autumn (Paper I).

2.2. Viiankiaapa mire

The Viiankiaapa mire is a nutrient-rich aapa-type patterned fen with distinctive string and flark patterns that have formed perpendicular to the flow direction of the mire water (Foster *et al.* 1983). The Viiankiaapa mire started to develop after the Late Weichelian, about 10 000 years ago (Suonperä 2016). The sediments underlying the peat mainly consist of aeolian sands and braided river sediments (Lappalainen 2004, Paper I). Sandy sediments are covered with gyttja (Lappalainen 2004) deposited during the Ancylus Lake phase about 10 300–10 200 years ago (Åberg A.K *et al.* 2017). Gyttja is covered by coarse detritus gyttja deposited before overgrowth of the lake stage (Lappalainen 2004). The lowermost peat layers consist of *bryales* peat, which changes upwards to a more mixed composition of *carex–bryales* peat with varying proportions of *carex* (Lappalainen 1970). The deposition rate of peat has been about 0.6 mm year^{-1} (Lappalainen 2004). The Viiankiaapa mire forms a habitat for multiple possibly groundwater-influenced plant species (Hyvärinen *et al.* (2019) IUCN classification in brackets), such as *Hamatocaulis vernicosus* (near threatened, NT), *Hamatocaulis lapponicus* (vulnerable, VU), *Meesia longiseta* (endangered, EN) and *Saxifraga hirculus* (vulnerable, VU) (Kulmala 2005, Eurola and Huttunen 2006).

2.3. The River Kitinen

The River Kitinen is a tributary of the Kemijoki river, which discharges into the Gulf of Bothnia (Fig. 1). The River Kitinen has been regulated since the 1970s by hydroelectric power plants (Alanne *et al.* 2014), which has changed the hydrological settings of the free-flowing river into regulated pools separated by hydroelectric power plants. The hydroelectric power plants have been used for electricity production and simultaneously to regulate the spring floods that used to cause economic damage to villages along the river shores. Regulation reduced the gradient of the river and simultaneously caused a rise in the river stage behind the dams of the hydroelectric power plants. Regulation also affected the groundwater–surface water interactions, since the rise in the river stage changed the locations of the groundwater discharge areas in the river banks and decreased riverine flooding.

3. Materials and methods

3.1. Materials

The study was performed with complex multiple source datasets that included different observations from variable sources (Fig. 2), mainly from AA Sakatti Mining Oy, NLSF, the Geological Survey of Finland, Kemijoki Oy, the ELY Centre and several unpublished reports. The quality of the datasets varied considerably, which was considered in model construction. In addition, new data were collected during the study, including groundwater table observations and monitoring data, ground penetrating radar (GPR) profiling, thermal infrared imaging, the stable isotope composition of water and hydrogeochemical data.

The datasets used for constructing the 3D geological models presented in Åberg A.K. *et al.* (2017) and Åberg A.K. *et al.* (2020) were compiling data from multiple sources, including a till geochemistry dataset, multiple drilling datasets from AA Sakatti Mining Oy, peat drillings, bedrock outcrops, excavated exposures, GPR profiles, as well as bedrock maps and surficial deposit maps from the Geological Survey of Finland. The model surface was based on a two-metre-resolution LiDAR DEM (light detection and ranging digital elevation model) produced by NLSF. In addition, the pre-regulation topography was recreated for flood modelling and for groundwater flow modelling of the pre-regulation groundwater flow. A base map of NLSF from 1989 and a river cross-section from Huokuna (1991) were used to construct the topography of the gravel intake area and shore area, which was covered with water after regulation (details presented in Paper III).

Groundwater table measurements were available from both automatic monitoring stations and manual observations. The latter included data from reports in 1988 (Lapin vesi- ja ympäristöpiiri 1988, unpublished report) and 1995 (Lapin ympäristökeskus 1998, unpublished report), and more recent data from a field campaign in 2015, presented in Paper I. Automated monitoring station data originated from AA Sakatti Mining Oy datasbase in 2012–2015. Groundwater table observations were used to calculate and estimate groundwater recharge and also to calibrate all the 3D groundwater flow models. Surface water observations were derived from a 1989 map and a LiDAR DEM from 2010–2015. Surface water observations from the LiDAR DEM were used to define the surface water flow directions and calibrate the groundwater flow models.

The hydraulic conductivities of Quaternary sediments were defined on the basis of grain-size analyses conducted with the Saurbrey method (Sauerbrey 1932) and slug-tests (Golder Associates 2012, unpublished data; SRK, unpublished data, 2019; AA Sakatti Mining Oy, unpublished data, 2019). The hydraulic conductivity of the fractured bedrock was interpolated from hydrogeological testing in boreholes, including packer, spinner and constant head tests (SRK, unpublished data, 2019), along with two slug tests (Golder Associates, unpublished data, 2012).

The locations of modelled groundwater discharge areas in the eastern river shore were confirmed with thermal infrared imaging (TIR) and the stable isotopic composition of water (Paper I). TIR data were acquired during fieldwork with an unmanned aerial vehicle (UAV). Samples for stable isotopic composition analysis were collected in multiple fieldwork campaigns and the data are presented in Lahtinen (2017), Paper I and in Bigler (2019).

River stage and river discharge data acquired from Kemijoki Oy were used to study the pre-regulation and present hydrological settings of the study area, and in flood modelling they were used to define the pre-regulation flood distribution (Paper III).

The locations of the examined groundwater-influenced species (*Hamatocaulis lapponicus*, *Hamatocaulis vernicosus* and *Saxifraga hirculus*) and flood-dependent species (*Carex microglochin*, *Moehringia lateriflora* and *Elymus mutabilis*) were acquired from the Eliölajit database of the Finnish Environment Institute (SYKE, unpublished data) and the AASMOy biological database (2021, unpublished data). The distributions of the aforementioned species were compared with the modelled regulation-influenced change in the groundwater table, changes in groundwater discharge areas between pre- and post-regulation models, and the simulated pre-regulation flood coverage (Paper III). Simultaneously, the relationship between the altitude of the groundwater table and the present distribution of the plant species was examined.

3.2. Methods

This doctoral study was completed with multiple different methods that were used to characterize the present and pre-regulation hydrological settings of the study area and evaluate its vulnerability to mining practices. The main methods included 1) hydrostratigraphic 3D modelling (Papers I–III), 2) 3D groundwater flow modelling (Papers I–III) used to define an adequate level of hydrostratigraphic detail (Paper II) and the present and pre-regulation groundwater flow and recharge/discharge patterns (Paper III), 3), flood modelling (Paper III), and 4) characterization of the hydrological features that may affect the threatened GIE within the study area (Paper III). Major workflows are presented in Fig. 2.

3.3. 3D Hydrostratigraphic modelling with Leapfrog Geo (Papers I, II and III)

The hydrostratigraphic models based on 3D geological modelling were generated with Leapfrog Geo (Seequent Ltd 2020). The modelling, based on a combination of explicit modelling and implicit modelling, is presented in more detail in Åberg *et al.* (2017) and Paper II. The datasets used to generate the hydrostratigraphic units were mainly from the Kersilö database (Åberg A.K. *et al.* 2017) and drilling data and hydraulic conductivity data were obtained from AA Sakatti Mining Oy. The 3D geological models were simplified as hydrostratigraphic models by excluding units with the smallest and most uncertain distributions (Papers I–III). The 3D geological model was updated multiple times based on the results of groundwater flow models, new observations and drilling data that were acquired during this study.

The selection of hydrostratigraphic units for the surficial deposits was mainly based on the separation of glacial till (3 units) from interlayered sorted sediments (4 units). In addition, a basal unknown sediment unit and two peat units were used as hydrostratigraphic units (Fig. 3). It was assumed that the hydraulic conductivity of till is generally lower than that of sorted sediments (1.2×10^{-6}–4.3×10^{-3} m s^{-1}; Paper II). However, the K of till was highly variable (5.0×10^{-8} to 8.3×10^{-5} m s^{-1}; Paper II), and some of observed high conductivity sandy tills act as aquifers rather than aquitards. Simultaneously, it was acknowledged that major hydrostratigraphic units consisted of heterogeneous material, which was considered in the parametrization of the groundwater flow models. The bedrock was first created with one (Paper I), then with two (Paper II) and lastly with three units (Paper III). The bedrock in Paper III is comprised of clay-type weathered bedrock with assumed low conductivity, grus-type weathered bedrock with assumed intermediate hydraulic conductivity and a fractured bedrock unit with variable hydraulic conductivity based on packer and spinner tests. The fractured bedrock unit also included separate parameter units for major discrete faults classified into three groups: thrust faults, brittle faults and clay-filled faults. The assumption was that brittle faults have a relatively high K, thrust faults have a lower K and clay-filled faults the lowest K, which corresponded to the K of a clay weathered bedrock unit (Paper III). The peat of the mire was assumed to be homogeneous for simplicity in the first hydrostratigraphic model presented in Paper I. In later models (Papers II and III), the mire was modelled with two layers, including an upper less decomposed and lower more decomposed layer, edited in the groundwater flow model grid in the ModelMuse graphical user interface (GUI) (Winston 2009). The hydrostratigraphic models were revised multiple times based on new observations, GPR profiling, drilling data and groundwater flow model results.

3.4. 3D groundwater flow modelling with MODFLOW-NWT (Papers I, II and III)

The MODFLOW series (McDonald and Harbaugh 1988) is a finite difference modelling code calculating the groundwater table and flow

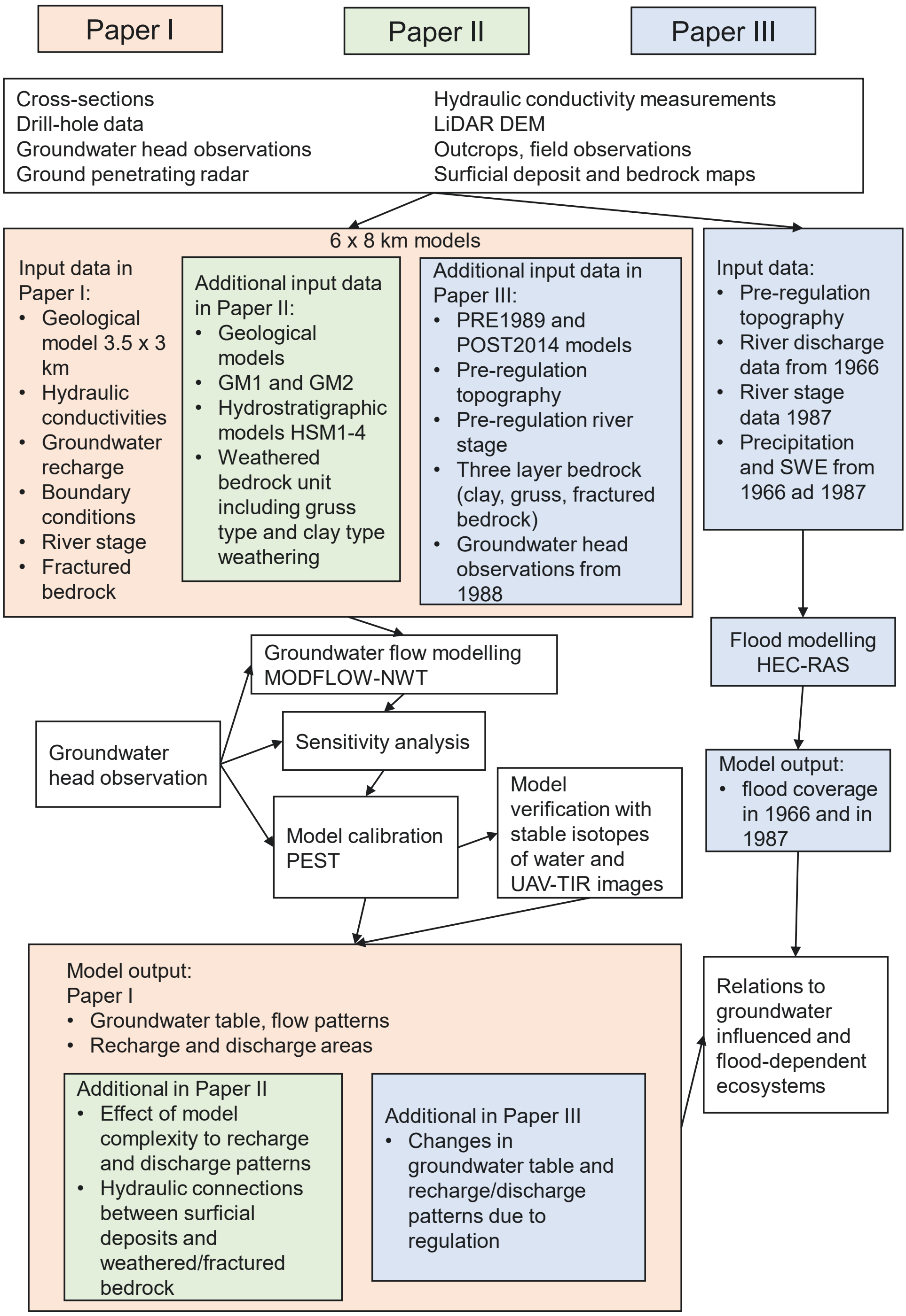


Figure 2. Schematic diagram presenting the workflow and relations of the methods used in Papers I, II, and III.

in each discrete cell, which has been used for years in groundwater flow modelling. The MODFLOW-NWT version (Niswonger *et al.* 2011), which uses the Upstream Weighting (UPW)

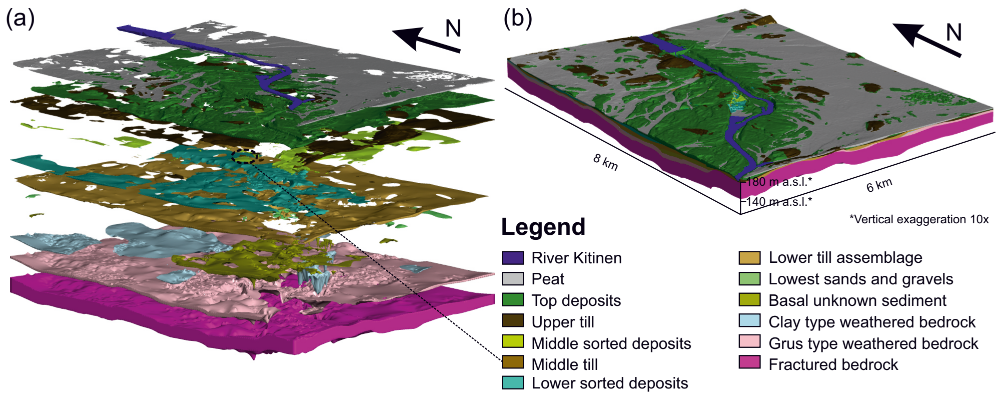


Figure 3. Geological model of the study area from Paper III constructed with Leapfrog Geo in (a) exploded view and (b) 3D view.

package with the Newton formulation, was chosen as the modelling code, since it enables the modelling of unconfined aquifers with a highly variable layer thickness and scattered unconfined units. The UPW package prevents a cell from being fully dry and keeps all cells active, which enables water table variation in a vertical direction between two or more stacked cells during model iterations. In contrast, in the widely used MODFLOW-2005 (Harbaugh 2005), wetting and drying of the cells is a challenging issue in thin scattered units. This is problematic, especially in thin-layered unconfined systems, which are common in formerly glaciated areas. MODFLOW-NWT has been successfully used with thin aquifers (Hunt and Feinstein 2012), and the results have been compared with analytical solutions (Zaidel 2013).

The hydrostratigraphic models in Papers I–III were first constructed with Leapfrog Geo (Seequent 2020 Ltd) and then converted to MODFLOW grids with the Hydrogeology tool of Leapfrog (further details in Papers I and II). The parameter zones of major hydrostratigraphic units were created in Leapfrog, and additional parameter zones were added in the ModelMuse GUI (Winston 2009), which was used for further groundwater flow model construction (Papers I–III). The hydraulic conductivities of the parameter zones were defined with interpolation and estimation from the results of grain-size analyses conducted with the Sauerbrey method (Sauerbrey 1932), slug tests, packer tests and spinner tests (further details in Papers I–III). Groundwater recharge was estimated based on the results of water table fluctuation (WTF) (Meinzer 1923) and episodic master recession curve (EMR) (Nimmo *et al.* 2015) methods.

The groundwater flow models in Papers I–III were calibrated with PEST (Doherty 2015). The parameter estimation method was used in Papers I and II and the stochastic random parameter method RANDPAR1 (Doherty 2018) in Paper III. In parameter estimation, PEST was used to find the single optimal parameter set that had the best possible fit between observed and simulated groundwater heads. In contrast, in the random parameter method RANDPAR1, multiple models with different parameters are run and their results are inspected to find the best model, which has as good a fit between observations and simulated heads as possible and reasonable parameter values compared to the measured or estimated *K*.

The groundwater flow model results were verified with the stable isotopic composition of water (Papers I and III) and with particle tracking (Paper II). In Paper II, MODPATH (Pollock 1994) was used to verify the flow paths of the observed isotopic compositions of water. The simulated flow paths were compared with the isotopic composition of springs on the river shore. The simulated groundwater discharge areas were also visually compared with the distribution of groundwater-influenced species in the mire area, and with groundwater discharge areas on the river shore observed with UAV-TIR in Paper I.

3.5. 2D flood modelling with HEC-RAS and flood frequency analysis (Paper III)

Flood modelling was used to study the pre-regulation flood coverage of the River Kitinen and to examine its effect on the hydrology of the Viiankiaapa mire. Flood modelling was performed using HEC-RAS with 2D models (Brunner 1995, Brunner 2016). The HEC-RAS model calculated the river stage based on river discharge data with the diffusion-wave equation (Brunner 2016). The Manning's roughness value of the river bottom is the most important parameter, which can be used to calibrate the model if river stage or discharge observations are available.

Flood modelling was performed for two floods, 12–28th May 1966 and 12–25th May 1987, based on available river discharge (Kemijoki Oy, unpublished data) and river stage data (Huokuna 1991), respectively. River discharge data from 1966 were used to create a rating curve, which was then used to convert the 1987 river stage data to 1987 river discharge data. The converted 1987 river discharge data were used to simulate the flood coverage of May 1987, which was then compared with the natural state of flooding defined with flood frequency analysis. The recurrence interval of the 1966 flood was calculated with Log Pearson type III and Weibull methods (Viessman and Lewis 2003). In addition, the recurrence interval was calculated for the maximum river discharge value of the 1987 flood to examine its relationship with pre-regulation flooding.

3.6. TIR imaging with UAV (Paper I)

The TIR survey of groundwater discharge areas was based on the temperature difference between discharging groundwater and surface water (Rautio *et al.* 2018). Since the groundwater temperature is rather stable and usually close to the annual average air temperature, groundwater discharge can be observed as an anomaly compared to the surface water if the temperature difference is large enough.

The TIR survey was used to identify groundwater discharge areas in the shore of the River Kitinen. The survey was performed with a UAV equipped with TIR and RGB cameras. The technical details are presented in Paper I. The UAV-TIR study was performed in August, when the difference between the surface water (>15 °C; Paper I) and groundwater temperatures (3–4 °C; AA Sakatti Mining Oy, unpublished data, 2015) was greatest, and groundwater discharge areas were possible to observe as cold anomalies from TIR images. The observed groundwater discharge areas were compared with groundwater flow model results to evaluate the models.

3.7. Stable isotopic composition of water (Papers I, II and III)

The stable isotopic compositions ($\delta^{18}O$ and δD), as well as *d*-excess values, have been used for years to determine the surface water and groundwater fractions from water samples (Hunt *et al.* 1998, Clay *et al.* 2004, Rautio 2015). When water is exposed to evaporation, its starts to be depleted of lighter isotopes and its composition deviates from the isotopic composition of meteoric water, which usually has a similar composition to groundwater (Gat and Gonfiantini 1981). Surface water bodies are usually exposed to evaporation and fractionated with heavier isotopes. If the isotope composition end members sufficiently differ, the isotopic composition can be used to distinguish groundwater from surface water (Gat and Gonfiantini 1981, Krabbenhoft *et al.* 1990, Kendall and Coplen 2001, Rautio and Korkka-Niemi 2015).

The stable isotopes $\delta^{18}O$ and δD and *d*-excess values were used to characterize different water types and their possible origin within the study area in Paper I. Stable isotopes were also used to verify the groundwater flow model in Papers II and III. The stable isotopic composition was assumed to remain unchanged during groundwater transport (Gat 2010) and thus reflect the composition of recharging water. Majority of isotope samples used in this study were taken during late summer and early autumn in order to ensure that the isotope signal from snow melt was negligible (Isokangas *et al.* 2017). In Paper II, MODPATH (Pollock 1994) particle tracking was used with stable isotopes to investigate the flow paths of different isotope compositions and to compare the results with observed stable isotope composition values in groundwater discharge areas in the river banks. In Paper III, stable isotopes of water were used to verify the groundwater flow model results in the Matarakoski area (Fig. 1) to examine how the construction of the Matarakoski power plant has affected the present groundwater flow paths.

4. Results

4.1. Results of Paper I

The groundwater flow modelling results indicated that mire water from Viiankiaapa flows towards the River Kitinen and discharges locally within the mire area and in the shores of the river. The groundwater flow direction in the western part of the Viiankiaapa mire was observed to gradually change during spring from an E–W direction to a more NE–SW direction. Groundwater table fluctuation was related to the spring thaw and higher recharge rate in the northern part of the model area. The model results indicated that groundwater recharge in the mire area was related to topographical variation and subpeat sediments. Groundwater recharge was observed in groundwater monitoring wells as groundwater table variation in the river banks and in the mire area.

Complex hydrostratigraphy considerably affected the groundwater flow patterns, since high variation in hydraulic conductivities was present, and multiple scattered till units were observed with scattered sorted sediment units. In addition, bedrock fractures and faults locally affected the groundwater table and flow and discharge patterns.

The stable isotopic composition of water and UAV-TIR survey indicated that groundwater discharge occurred in the eastern shore of the River Kitinen and eastern fringe of the Viiankiaapa mire. Stable isotopes and groundwater flow modelling results indicated that the heterogeneity of the fractured bedrock and peat should be studied further in future modelling to improve understanding of the hydraulic connection between the mire and fractured bedrock within the study area.

4.2. Results of Paper II

The effect of hydrostratigraphic complexity was evaluated with four different hydrostratigraphic models, which indicated that the addition of geological detail to the groundwater flow model increased the model fit, especially if groundwater monitoring wells are screened at different lithological units in different depths. Explicit modelling with Leapfrog Geo was found to be an effective but time-consuming method for modelling highly heterogeneous Quaternary systems with weathered and fractured bedrock. MODFLOW-NWT was found to be suitable for modelling groundwater flow with complex Quaternary sediment package, since it allowed modelling with unconfined scattered units having a highly variable layer thickness.

The results of the four models indicated that the addition of hydrostratigraphic detail created more complex groundwater recharge and discharge patterns and increased the vertical flow if high variation in hydraulic conductivity was present. In contrast, groundwater flow was predominantly horizontal in models in which Quaternary sediments and bedrock were simplified as one layer per unit. The calibration of the complex models was more challenging, and low sensitive parameters needed to remain unchanged during calibration, causing greater uncertainty in the calibrated parameters and the modelling results.

The creation of complex models was recommended if the research interest is related to detailed understanding of groundwater flow patterns in highly heterogeneous systems, or their interaction and connections with surface waters, and enough time and data are available for the modelling.

4.3. Results of Paper III

The regulation of the River Kitinen and especially the construction of the Matarakoski and Kelukoski hydro-electric power plants in 1995 and 2001, respectively, affected the hydrological settings of the Viiankiaapa mire by reducing the hydraulic gradient towards the river. The results of flood models indicated that regular flooding affected the westernmost part of the mire before the regulation of the river. The recurrence interval of the 1966 flood, with a maximum discharge rate exceeding 900 $m^3 s^{-1}$, was 11 years, and the recurrence interval of a flood comparable to that in 1987, with maximum discharge rate exceeding 600 $m^3 s^{-1}$, was two years before river regulation. The flood coverage model for 1987 corresponded with observed floodplain sediments. The rise in the river stage reduced the hydraulic gradient towards the river, increasing the groundwater table in the river banks and western part of the Viiankiaapa mire. River regulation increased the groundwater discharge areas in mire, changed the spring locations in the river shore to a higher altitude, and reduced groundwater discharge into the River Kitinen.

The groundwater flow models and the stable isotopic composition of water indicated that the constructed Matarakoski dam changed the groundwater flow directions only locally next to dam. The studied flood-depended plant species declined due to the reduction of flooding maximums after river regulation. The regulation-influenced groundwater table rise covered almost half of the current habitats of all studied groundwater-influenced mire plant species. The occurrences of *Hamatocaulis vernicosus* and *Hamatocaulis lapponicus* appeared to be related to the high water table and groundwater discharge areas in Viiankiaapa. The model results indicated that the Viaankiaapa mire is partly human influenced due to regulation of the River Kitinen.

5. Discussion

5.1. General overview of the groundwater flow patterns in the study area

Groundwater circulation in the study area is highly complex due to the heterogeneous hydrostratigraphy. Groundwater recharge and discharge within the mire area are controlled by the composition of subpeat sediments and peat, as well as topographical variation. Groundwater recharges in the river banks and in the forested areas and topographical highs within the mire area. Groundwater mainly flows in high conductivity zones of fluvial sands and gravels (Fig. 4) and in ancient river channels. Bedrock weathering, fractures and faults control groundwater flow in deeper circulation. Local topographic variations and high variation in hydraulic conductivity values add complexity to the flow patterns, and local perched and confined settings can exit on the river banks (Paper II). Groundwater discharges locally in mires and in the shores of the River Kitinen, and also flows in deeper circulation in weathered and fractured bedrock (Fig. 4). Recent groundwater with an evaporated component has been observed in fractured bedrock up to a depth of 100 m (J. Karhu *et al.*, AASMOy, unpublished report, 2020), indicating a connection with shallow groundwater and groundwater in the upper part of the crystalline bedrock. (Paper II).

5.2. Suggested groundwater flow modelling workflow for recently glaciated areas

Describing the workflow (Fig. 5) is important, since it makes it easier to learn how to produce an adequate groundwater flow model for research purposes. Commercial groundwater flow model software includes tutorials and courses for learning the basics of the software. On the contrary, open-source software usually includes limited tutorials and courses. However, in both cases, the tutorial examples are usually simple and easy to understand. In reality, modelling is much more challenging and depends on the study site, available data and definition of the model boundaries. GUIs make the construction of groundwater flow models easier, increasing the risk of misuse of mathematical codes without understanding the limitations of the models (Younger 2008). When a simple but adequate workflow is presented in a scientific article, it makes the learning process faster and gives more time to concentrate on the hydrostratigraphic detail of the model. This detail is especially important in areas where the hydrostratigraphy is complex and hydraulic conductivity variation between the units is prominent. Sharpe *et al.* (2002) created a progressive hydrogeological modelling approach for glaciated terrain, and Ross *et al.* (2005) generated a common stratigraphic framework for hydrogeological applications in Quaternary hydrogeological settings. A workflow based on data standardization in hydrogeological studies has also been suggested, e.g., by Allen *et al.* (2008). The workflow presented in this study is suggested for use in areas of weak glacial erosion (Fig. 1), in which the presence of complex hydrostratigraphy with preserved weathered bedrock is likely. The following steps are suggested for the construction of a detailed groundwater flow model:

- Step 1: Collection of all available data to construct the hydrostratigraphic units, including till geochemistry, drill hole data, grain-size analyses, groundwater monitoring well data, hydraulic conductivity measurements and outcrop data.
- Step 2: Consideration of the datasets based on the original study targets to avoid misinterpretation from biased datasets, e.g., till geochemistry where till samples dominate.
- Step 3: Definition of the major hydrostratigraphic units mainly controlling groundwater flow. Use of major glacial till units and interlayered sorted sediment units as hydrostratigraphic units and consideration of the internal high variation in *K*. Additional consideration of weathered bedrock units and delineation of these based on their estimated hydraulic properties. Omission of units that have an uncertain/limited distribution. Leapfrog Geo can be used for modelling hydrostratigraphic units and converting geological/hydrostratigraphic models to a MODFLOW groundwater flow model grid.
- Step 4: Selection of the model code, model boundary and boundary conditions based on available data and research interests. MOD-

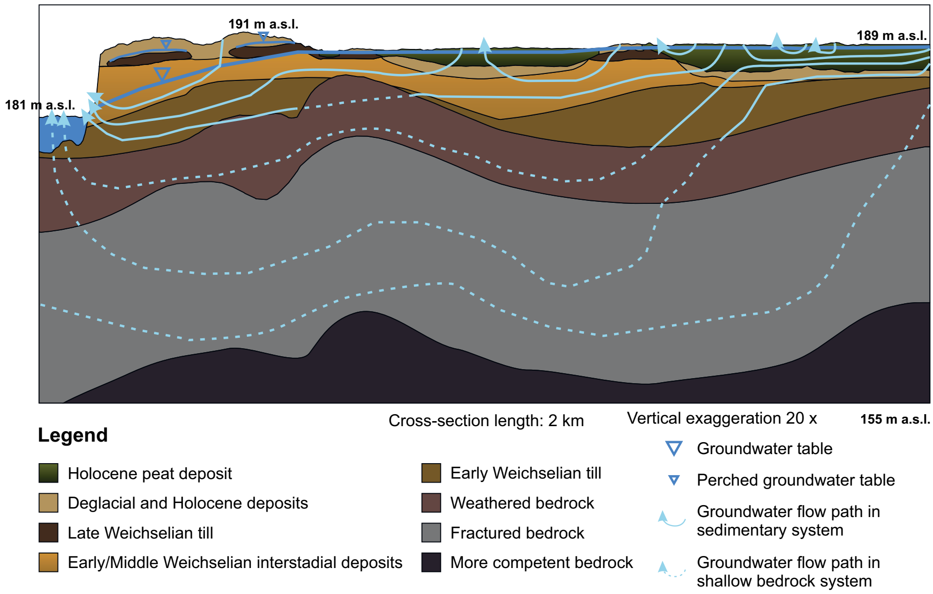


Figure 4. Simplified conceptual model of groundwater flow paths in river banks and in the western part of the Viiankiaapa mire. The stratigraphic units are based on Åberg A.K. *et al.* (2020) and Paper II.

FLOW-NWT is suitable for highly heterogeneous study areas with unconfined settings.

- Step 5: Testing first with a simple groundwater flow model and then after increasing the hydrostratigraphic detail during further model development. Models can be calibrated with PEST using parameter estimation or the random parameter method with RANDPAR.
- Step 6: Validation of the model by comparing the results with other available datasets e.g. the stable isotopic composition of water, observed groundwater discharge areas, thermal infrared imaging, the habitats of groundwater indicator species, GDEs or other available data. If the variation in the isotopic composition of water is notable, MODPATH software can be used to calculate the flow paths for different isotopic compositions.
- Step 7: Adjustment of the model hydrostratigraphic units based on the groundwater flow model results/calibration or validation results. If the results strongly deviate from observations, something is intervening from the hydrostratigraphy or the boundary conditions. The collection of new observations and measurements close to the poorly fitting areas is suggested.

Analogous weak glacial erosion areas with a possibly complex stratigraphy suitable for the workflow presented above exist in other areas in Scandinavia (Ebert *et al.* 2015) and North America (Kleman and Glasser 2007, Atkinson *et al.* 2014). The presented workflow is also useful in areas with thick glacial drift in former glacial margin areas (Kleman *et al.* 2008) consisting of multiple till layers with occasional interbedded sorted sediments. This type of workflow could also be suitable for modelling the groundwater flow paths in alpine systems, such as in moraine talus fields (Roy and Hayashi 2009, McClymont *et al.* 2010).

5.2.1. Adequate detail in groundwater flow modelling of formerly glaciated area vs. modelling limits

Groundwater flow models are always simplifications of reality. Variation in hydraulic conductivities is important to include in models, since it directly affects the distribution of groundwater recharge and discharge areas (Fig. 6). However, the scale of the model, research objective, project schedule and the availability of subsurface observations, e.g., drilling data, defines how detailed a layer structure it is possible to construct. In formerly glaciated areas, the interpretation of variable drilling data (e.g., installation of observation wells, till geochemistry) can cause challenges in defining actual hydrostratigraphic units due to the different original targets and definitions of geological units. Interlayered sorted sediments and till create highly complex hydraulic conductivity patterns, since the hydraulic conductivity of sorted sediments tends to be orders of magnitude higher than that of till (e.g., Freeze and Cherry 1979). Simultaneously, the hydrostratigraphic units tend to be scattered due to the variation in sedimentation and erosion rates during the glaciation and deglaciation cycles (Atkinson *et al.* 2014). The scattered nature of the hydrostratigraphic units makes groundwater flow modelling challenging, as unconfined, confined and perched groundwater units may be present. In addition, groundwater can exist at multiple levels, which has been observed, for example, in the Hannukainen area (Salonen *et al.* 2014).

First, the most important aspect is to define the large-scale units that affect groundwater flow the most in the selected model area. In this study, the definition of the major units was based on the separation of glacial tills and interlayered fluvial/glaciofluvial deposits (Åberg A.K. *et al.* 2017, Paper II). Although the units were presented as single layers (e.g., all braided river deposits within one unit), internal variation was added with the interpolated *K*. However, the simplification of small-scale units is always needed, depending on the research objective and scale of the model (Barthel and Banzhaf 2016). During the development of the groundwater flow model, more detail can be added to the hydrostratigraphic model to enhance the accuracy of the model results. Groundwater flow modelling can be used as tool for recognizing the areas of poor fit needing reconstruction in hydrostratigraphic models. However, it should be noted that adding hydrostratigraphic units does not fix the problems if they exist in the boundary conditions, as discussed earlier by Doherty (2015). Simultaneously, the parameters of various hydrostratigraphic units may interact and compensate for the errors in each other, as noted by Jaros *et al.* (2019).

High variation in hydraulic conductivity between layers can cause non-convergence in models, since water exchange between cells causes excessive numerical errors and the solver tolerance is not achieved during model iterations. In Quaternary sediments, high variation in hydraulic conductivities is common, which can limit the model accuracy if realistic variation cannot be used due to convergence problems. For example, hydraulic conductivities in the models of this study varied from 10^{-9} to 10^{-3} m s^{-1}. Parameter estimation indicated that the models had convergence problems when parameter values went below 10^{-9} m s^{-1} during iterations.

MODFLOW-NWT allows simulation with the water table below the cell bottom, but not if the water table is below the model bottom (see Niswonger *et al.* 2011 for further details). This can be an issue in study areas where the bedrock is assumed to be impermeable and the surficial deposits are thin or highly variable in altitude. On the contrary, MODFLOW-NWT appeared to tolerate high variation in cell thickness, which is useful for modelling of scattered or pinched units.

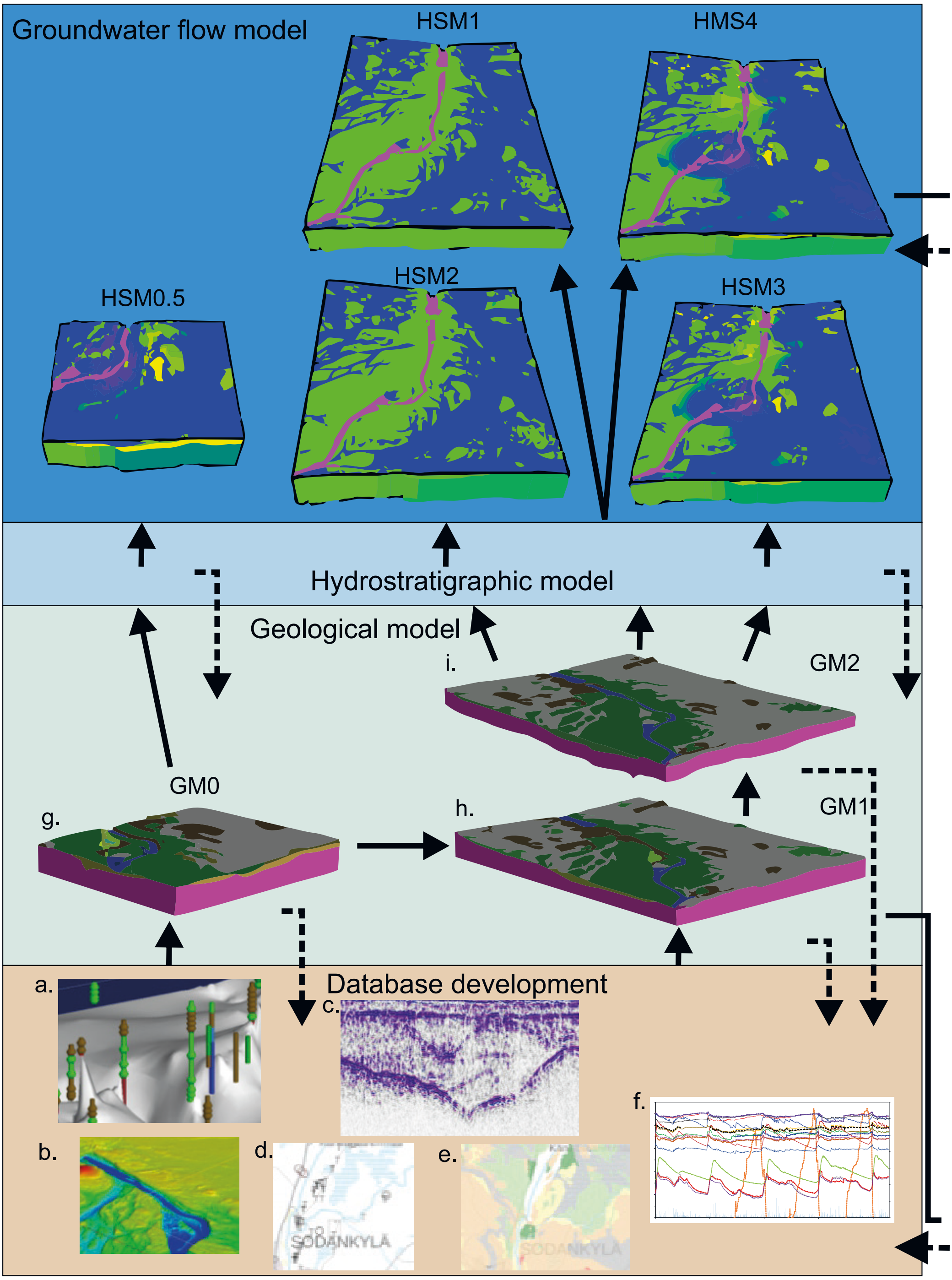
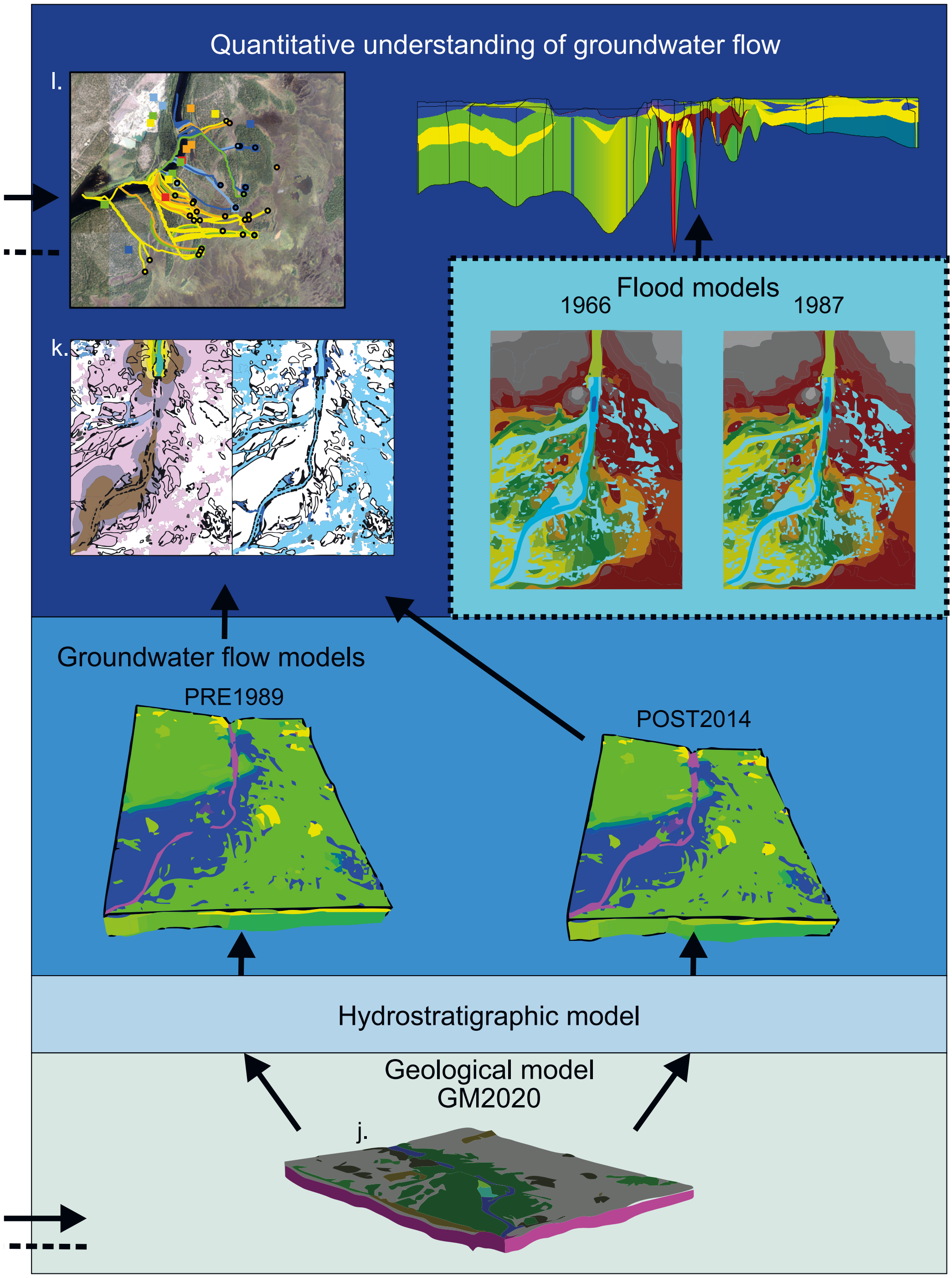


Figure 5. The workflow and model evolution in this study. The classification of the main phases is derived from Sharpe *et al.* (2002). Hydraulic conductivity variation in groundwater flow models is explained in Paper II. Figure sources: a. Targeting till geochemistry dataset in Leapfrog Geo; b. LiDAR DEM modified after NLSF; c. GPR profile used for the construction of the geological models; d. drill hole data source: Hakku database https://hakku.gtk.fi/fi/locations/search; e. surficial deposit



maps source: Hakku database https://hakku.gtk.fi/fi/locations/search; f. groundwater table and the snow water equivalent (SWE) variation figure modified from Paper I; g. modified from Åberg A.K. *et al.* (2017); h., i. & l. modified from Paper II; j. & k. modified from Paper III.

Moreover, MODFLOW-NWT appeared to tolerate multiple unconfined or convertible layers, allowing higher hydrostratigraphic variation in the vertical direction. This is useful in glaciated areas where thin till and sorted sediments alternate.

Simple models appear to be reasonable for water balance-based studies (Hudon-Gagnon *et al.* 2015). Information criteria-based evaluation, e.g., Akaike information criteria (AIC) (Akaike 1974) or the Bayesian information criterion (BIC) (Schwarz 1978), could be used to select an adequate level of detail for groundwater flow models. The assumption is that adequate models have as few calibrated parameters as possible to represent the system with an adequate approximation of the measured data (Engelhardt *et al.* 2014). Information criteria based on evaluation methods appear to favour simpler models (Foglia *et al.* 2007, Engelhardt *et al.* 2014). In addition, the more detailed the model is, the less sensitive the parameters will be to groundwater table variation, making the calibration of complex models with multiple parameters challenging. Paper II indicated that the model fit in groundwater wells increased and more plausible groundwater flow patterns were obtained when more complex models were used. More complex models are recommended if the research objective is related to recharge/discharge patterns, since high variation increases the vertical flow component and disperses recharge/discharge patterns compared to simpler models (Fig. 6).

In groundwater flow modelling, relatively simple codes such as MODFLOW (McDonald and Harbaugh 1988) are easier to use and the model results are easier to interpret. However, important groundwater–surface water interactions should not be oversimplified. The MODFLOW DRN package is relatively straightforward for modelling groundwater discharge. MODFLOW DRN assumes that all water rising above a selected altitude, such as topography, escapes from the model as groundwater discharge (McDonald and Harbaugh 1988). The groundwater discharge locations should be known prior to modelling, and DRN should only be used in these locations to avoid overestimation (Batelaan and De Smedt 1998). For example, TIR imaging can be used to locate the groundwater discharge areas (Paper I). More detailed surface water–groundwater interactions could be modelled with coupled models such as Parflow (Kollet and Maxwell 2006) and HydroGeoSphere (Therrien *et al.* 2010), which include the surface water and unconfined zone flow physics in more detail. However, constructing and running coupled models requires much more effort than modelling with MODFLOW.

A transient model instead of a steady-state model could be used for detailed modelling of groundwater recharge during the spring thaw. In the areas where groundwater flow directions change, transient modelling is strongly recommended (Younger 2008). In this study area, transient modelling could enhance the detail understanding of groundwater and mire interactions. It could be used for modelling observed seasonal wetland areas that replenish from perched groundwater (Salonen 2020). However, in models with complex hydrostratigraphy, the definition of parameters needed for transient models might include more uncertainty and possible misinterpretations in the model results.

5.2.2. Adequate details in weathered and fractured bedrock

The weathering process of crystalline metamorphic and igneous rocks leads to a weathering profile with variable hydraulic conductivity, especially if chemical weathering is present (Wright 1992). Understanding of the weathering profile of crystalline bedrock is important, since the hydraulic conductivity can vary prominently depending on the material or weathering rate (Welby 1981, Schoeneberger and Amoozegar 1990,

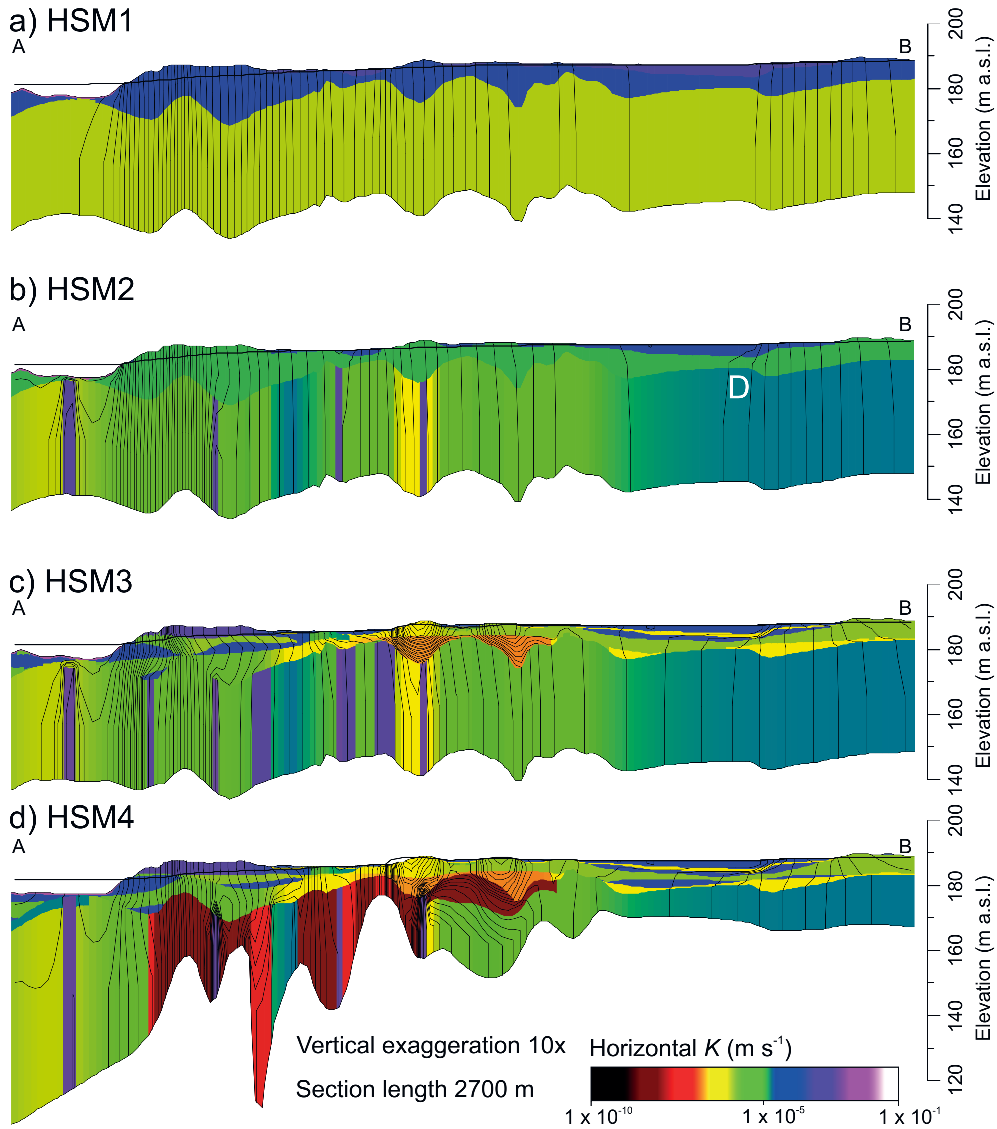


Figure 6. Cross-sections of the HSM models with hydraulic head contours having a 10-cm interval. a Model HSM1; b Model HSM2. The white D indicates an increase in the vertical flow component due to the higher *K* in the bedrock. c Model HSM3; d Model HSM4. The location of cross-section A–B is presented in Fig. 1 in Paper II. Reprinted with CC BY-NC 4.0 license of Open Access Articles from Paper II.

Wright 1992, Maréchal *et al.* 2004). Hydraulic conductivity variation in weathered bedrock also affects the interactions between the shallow groundwater and bedrock groundwater (Fig. 6). A relatively simple approach to defining the hydrostratigraphic units is to use a weathering index to separate clay-like highly weathered saprolite from less weathered, often sand-like grus-type saprolite (Hall *et al.* 2015). Chemical weathering with clay-like products creates low hydraulic conductivity (10^{-9}–10^{-7} m s^{-1}, Welby 1981, Schoeneberger and Amoozegar 1990). In contrast, if the weathering product is sandy or till-like grus-type saprolite, the hydraulic conductivity can be orders of magnitudes higher (~10^{-6} m s^{-1}, Schoeneberger and Amoozegar 1990, Maréchal *et al.* 2004).

The upper part of the bedrock underlying the saprolite tends to be highly fractured (Guihéneuf *et al.* 2014, Boisson *et al.* 2015), being the most conductive zone in crystalline bedrock (10^{-6}–10^{-5} m s^{-1}, (Maréchal *et al.* 2004). In addition, the connection between the fractures affects the hydraulic conductivity, since only the connected fractures enable groundwater flow (Singhal and Gupta 1999). However, variation in hydraulic conductivity at the fracture scale and inside a fracture is difficult to measure.

The connection of groundwater in Quaternary sediments and in bedrock can be modelled with MODFLOW if the fracturing of the bedrock can be assumed to behave like continuous porous media (Singhal and Gupta 1999). In fractured crystalline bedrock, large-scale fractures or faults can be modelled with a parameter zone defining the distribution of a fracture or a fault (Paper II). Large-scale conductivity zones should be defined at the beginning of modelling, and more detail can be added during later model development. In parametrization, it should be noted that measured hydraulic conductivities, e.g., with packer tests, always represent the average of multiple fractures.

5.3. Groundwater recharge and soil frost

The MODFLOW recharge package is a simple tool to simulate groundwater recharge if only an estimated value of groundwater recharge is needed. In cold climate areas, soil frost can impede groundwater recharge during winter, and soil frost distribution can be variable and driven by topography (Hayashi *et al.* 2003). In addition, some of the snow cover evaporates or sublimes, and using SWE for recharge estimation can cause overestimation. In this study area, the spring thaw is usually quite abrupt and groundwater recharge appears to cause one maximum peak during the spring (Paper I). According to Lahermo (1970), slow thawing of soil frost prevents groundwater recharge and flood water infiltration. In contrast, during the melting of the soil frost, the recharge increases, causing the groundwater table to rise.

In the groundwater flow models presented in this study, the annual means of groundwater recharge were used in steady-state models and the effect of frost was omitted. However, SWE was considered in recharge estimation conducted with the WTF method (Meinzer 1923) and with the EMR method (Nimmo *et al.* 2015) calculated from groundwater monitoring data and SWE data (Paper I). Specific yield estimation for water table fluctuation methods was challenging due to the high heterogeneity of the Quaternary sediments. The SWE and soil frost could be considered in more detail if transient coupled surface water–groundwater models with snow package, e.g., HydroGeoSphere, were used (Schilling *et al.* 2019). Soil frost could also be simulated using time-varying hydraulic conductivity applicable in MIKE SHE (Hughes and Liu 2008).

5.4. Verification of groundwater flow modelling with δ^{18}O, δD and *d*-excess values

Groundwater flow modelling can be used to define the groundwater flow path, whereas stable isotope compositions of δ^{18}O and δD and *d*-excess values provide detailed information on the origin of water samples. δ^{18}O and δD compositions and *d*-excess values can be used to distinguish evaporated water from meteoric water (Craig 1961). The isotopes are used to calculate the mixing of the surface water and groundwater, since surface waters are affected by higher evaporation, which can be detected via the fractionation of heavier isotopes in water samples (Gat 1970, Hunt *et al.* 1996, Kortelainen 2007). While the isotopic composition of groundwater is usually close to the local meteoric water line, groundwater having an evaporated component can also be found (Paper I). $\delta^{18}O$, δD and *d*-excess values can also be used to delineate groundwater-dependent areas within peatlands (Isokangas *et al.* 2017).

At this study site, $\delta^{18}O$, δD and *d*-excess were used for model verification, since high variation in the isotope composition and the evaporated component was present. MODPATH (Pollock 1994) particle tracking was found to be a useful tool in model verification when high variation in the stable isotope composition was present (Paper II). However, since MODPATH is only based on advection, the mixing of the different compositions was not computed. The MODFLOW model could also be calibrated with the stable isotope compositions of water with solute transport modelling software such as MT3DMS (Zheng and Wang, 1999). $\delta^{18}O$, δD and *d*-excess can be used as conservative tracers when no fractionation occurs after the recharge (Stichler *et al.* 2008, Liu *et al.* 2014).

The $\delta^{18}O$ and δD composition indicated a heterogeneous and diffuse system (Paper I, Bigler 2019). Paper I indicated that some evaporated water occasionally infiltrates into the groundwater in the Viiankiaapa mire area and discharges via some springs in the shore area of the River Kitinen. Particle tracking with *d*-excess in Paper II indicated that the estimated source of the isotope composition is dependent on the distribution of units with high hydraulic conductivity. Simultaneously, the structure of the weathered/fractured bedrock and the distribution of faults and fractures and the impermeable model bottom affected the deeper circulation of groundwater (Paper II; Fig. 10).

5.5. The importance of understanding surface water and groundwater flow patterns in the early phase of mining projects

This study indicates that thorough understanding of the groundwater flow patterns, hydrostratigraphy and possible connections of shallow groundwater with surface water and bedrock aquifers would be beneficial to study in the early phase of mining projects. Salonen *et al.* (2014) pointed out that if subsurface structures are studied in adequate detail in the early phase of planning mining activities, potential environmental risks could be avoided during later mining practices. Hydrogeological studies could already be beneficial to conduct simultaneously with the exploration drilling phase. Morton and van Mekerk (1993) noted that while hydrogeological investigations and groundwater flow modelling are usually carried out to predict open mine dewatering practices, hydrogeological investigations should be started at the same time as geological investigations. The pollution of groundwater due to mining practices is generally well known phenomena, whereas the site-specific effect of mining activity on groundwater is often poorly understood (Younger 1997, Raghavendra and Deka 2015).

Open datasets such as till geochemistry data (Gustavsson *et al.* 1979, Shilts 1984) could be used for multiple purposes such as studying the glacial history of the area, constructing the hydrostratigraphy or prospecting the ore. It is useful to observe the structure of surficial deposits in the early exploration phase, since all observations are valuable data for baseline studies prior to mining activities. Moreover, Morton and van Mekerk (1993) emphasized that all exploration drilling records should include notes on observed water occurrences and volumes. Archival data such as water well records could be useful in constructing hydrogeological models. Even though they might be of low quality, their profitableness can be enhanced through careful development of the models (Sharpe *et al.* 2002). The construction of a 3D geological model and a groundwater flow model is giving valuable support for baseline studies and in the early planning stages of mining when enough data is available. Understanding of the surficial deposits directly linked to groundwater flow enhances understanding of water circulation and management at mining sites.

5.6. The importance of defining the initial condition for environmental impact assessment (EIA)

In EIA, it is important to define how the planned practices, such as mining, could affect the environment, animals, plants and human activities, among other effects, and to define the possible future risks (Worldwide Environmental Law Alliance 2010, Castilla-Gómez and Herrera-Herbert 2015). In Finland, EIA is required by law for the extraction of natural resources, including mining practices (Act on Environmental Impact Assessment 252/2017). The definition of the initial condition is important for distinguishing the environmental influences of the upcoming practices from present or previous anthropogenic influences or events. If the initial condition is understood well enough, the forthcoming changes can be defined and predicted better. In this study, the separation of previous influences, such as the regulation of the river and its influence on the mire, facilitated the EIA.

Natura 2000 assessment concentrates on the ecological protection of defined sites (Marandi *et al.* 2014, Kati *et al.* 2015). The Viiankiaapa mire is protected by the Natura 2000 network due to its large, aapa-type mire environments, which are assumed to be in a natural state, with fen patches that are habitats for several endangered and near-threatened plant and bird species (Hjelt and Pääkkö, 2006). The results of this doctoral study indicate that the western part of the Viiankiaapa mire has been influenced by the regulation of the River Kitinen by hydroelectric power plants since the 1970s. The most notable impact of the river regulation are the raising of the water table in the western part of the mire and in the river banks due to the river stage rise and reduction in the maximum river discharge rates and riverine flooding (Paper III). Comparison of the model results with the distribution of groundwater-influenced plant species in Paper III indicated that half of the present habitats of *Hamatocaulis vernicosus*, *Hamatocaulis lapponicus* and *Saxifraga hirculus* occurred within regulation-affected areas. The results of Paper III also demonstrated that the regulation of the River Kitinen has caused a decline in flood-dependent species on the river shores. It is crucial to understand previous anthropogenic influences in pre-feasibility or baseline studies to differentiate the environmental changes of the upcoming practices from initial influences.

6. Conclusions

Based on the results of this doctoral study, it is recommended to consider the complexity of Quaternary sediments and weathered/fractured bedrock in the 3D groundwater flow modelling and water management of future mining projects located in areas of weak glacial erosion. Greater complexity in 3D model structures yields more plausible groundwater recharge/discharge patterns. The main findings of the study can be summarised as follows:

A. Groundwater circulation within the study area is complex due to heterogeneous hydrostratigraphy, characterized by interlayered glacial till and fluvial and glaciofluvial sediments covering weathered and fractured crystalline bedrock. Aquifers tend to be scattered and mostly unconfined, although confined and perched settings occasionally occur within the study area. Groundwater recharge and discharge areas occur within the Viiankiaapa mire, and mire water is partly repercolated. Water infiltrating in the recharge areas of the mire is discharging in the mire area and on the shore of River Kitinen in the shallow circulation. Groundwater recharging in the riverbanks is mainly discharging into the River Kitinen.

B. Groundwater recharge, discharge and flow patterns within the study area are controlled by the high variation in hydraulic conductivity, the composition of subpeat sediments and topographic variation. The complexity of the hydrostratigraphy is also implied by high variation observed in the stable isotopic composition of water, indicating a heterogeneous and mixed origin of the waters. Verification of the groundwater flow models with the stable isotopic composition of water indicated that the addition of hydrostratigraphic detail to the models also affected the groundwater flow paths and the distribution of groundwater recharge and discharge areas in Quaternary sediments and weathered/fractured bedrock.

Altogether, the results of this doctoral study indicate that it is worth constructing a more complex geological/hydrostratigraphic model if high variation between units in hydraulic conductivities is present, if detailed understanding of groundwater discharge and recharge patterns is needed, and if sufficient data and time for modelling are available. The appropriate level of model complexity is dependent on the research question. In water balance studies, simple models can give as reasonable results as complex models. However, if detailed understanding of groundwater flow patterns is needed for research objective, models with greater hydrostratigraphic detail are recommended. This is especially suggested if mire areas or groundwater GDE or GIE are present.

C. The 3D groundwater modelling results indicated that the present state of the Viiankiaapa mire is not fully natural, since the regulation of the River Kitinen has reduced the flood coverage and hydraulic gradient towards the river and simultaneously raised the water table in western part of the mire. Furthermore, modelling results indicated that the reduction of the hydraulic gradient has reduced the groundwater discharge in the riverbanks and increased the discharge area in the mire. The distribution of the studied groundwater-influenced plant species in the Viiankiaapa mire appears to be related to the high water table and groundwater discharge areas within the mire. The regulation of the River Kitinen has stabilized the environment, which might be favourable for *Hamatocaulis vernicosus*. Pre-regulation observations would be beneficial for further conclusions.

D. A workflow comprising hydrostratigraphic and groundwater flow modelling was developed for baseline studies of mining development site in recently glaciated areas. The definition of the main hydrostratigraphic units controlling groundwater flow was considered first in the model construction phase. The main glacial till units and interlayered sorted sediment units, as well as weathered/fractured crystalline bedrock were used as hydrostratigraphic units. The bedrock was defined based on the estimated weathering profiles and fracturing rate: clay type weathered bedrock → grus-type weathered bedrock → fractured bedrock. More detail was added within hydrostratigraphic units in model parametrization, and hydrostratigraphic models were updated based on groundwater flow model and calibration results in an iterative manner. However, the higher the level of hydrostratigraphic detail, the more challenging the groundwater flow model calibration was, since the addition of more parameters tended to reduce the sensitivity of the parameters, causing more uncertainty in models.

E. Thorough understanding of the groundwater flow patterns, hydrostratigraphy and connections of shallow groundwater to surface water and possible bedrock aquifers is beneficial in the early phase of mining projects. The construction of a 3D geological model and 3D groundwater flow model should be a standard procedure in planning of water management at mining sites to achieve more comprehensive knowledge of water circulation.

F. Furthermore, the results of this study indicate that understanding of past and present anthropogenic influences can support the baseline or pre-feasibility studies to differentiate the environmental changes of the upcoming practices from initial influences. The results of this study imply that more detailed observation data, more detailed understanding of the groundwater circulation of the system and more detailed modelling will lead to a better overall understanding of the system.

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